Effect of Ionospheric Horizontal Gradient to GPS Signals at IPP

K Nagarajoo

Abstract ? GPS ray propagates at two carrier frequencies; L_1 at 1575.42 MHz and L_2 at 1227.6 MHz In this project, Jones 3D Ray Tracing program being used to determine the characteristics of the GPS ray as it propagates through the ionosphere. A numerical mathematical model *which is continuous and contains no* singularities has been used to represent the actual formation of the ionosphere in 3 dimensional (latitude, longitude and altitude). By using GPS ray tracing, it has been proved that the path of propagation for both L_1 and L_2 in the ionosphere is different. The point (latitude and longitude) where L_1 intersects at IPP is different than the point (latitude and longitude) of intersection of L_2. IPP or Ionospheric Pierce Point is the altitude in the ionosphere where the composition of electron density is greatest. It is also shown that the distance between the L_1 and L_2 at IPP over the equatorial region is greater than in the mid-latitude region. This is due to the difference in the composition of electron density in both these regions and also due to the presence of ionospheric horizontal gradient. In GPS, the presence of ionospheric horizontal gradient can effect the final GPS positioning if its' being ignored, especially the GPS positioning over the equatorial region.

Keywords: *GPS, ionospheric horizontal gradient, IPP and Jones 3D Ray Rracing.*

Global Positioning System (GPS) is a system that uses at least 28 Medium Earth Orbiting satellites to transmit precise microwave signals on two carrier frequencies, L_1 and L_2 at 1575.42 and 1227.6 MHz respectively, to the GPS receivers on the Earth. This enables the GPS receiver to determine the location, speed, direction and time anywhere and anytime on the Earth. After receives the signal, GPS receiver will compare the time taken to receive the transmitted signal from the satellite with the time that it suppose obtained from the measurement of distance from the receiver to the GPS satellite. The delay termed as group path or group delay due to the refraction of GPS signals that propagate through the ionosphere. This phenomenon is shown in Figure 1. The electron density in the ionosphere does cause to the refraction of GPS signals. However, this composition of ionosphere does varies diurnally, seasonally, timely and it also varies according to geographic location. Due to that, the ionospheric pierce point (IPP) or the altitude in the ionosphere where the composition of electron density is greatest does varies depending on those criteria stated earlier. Therefore, when the GPS carrier frequencies, L_1 and L_2, propagate through the ionosphere, the intersection altitudes or IPP of those carrier frequencies are different. Normally, the refraction of L_2 is always greater than L_1. This is also due to the presence of ionospheric horizontal gradient. The greater the gradient, the greater the distance between L_1 and L_2 at one particular altitude or IPP.

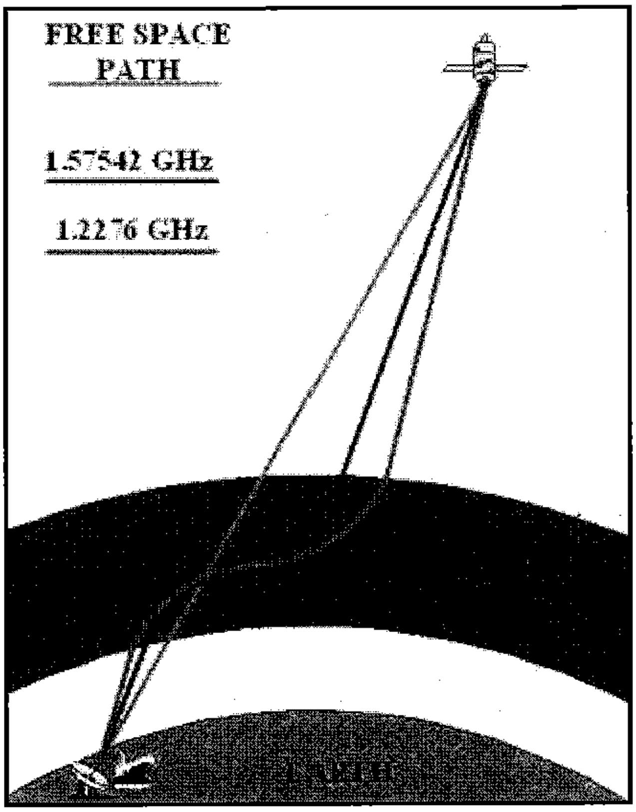

Figure 1 : GPS rays refracted when they propagate through the ionosphere (Ioannides R.T., 2002).

The ionosphere, which is found from the altitude of about 60km to about 2000km (Bilitza, 2001), contains up to four layers of free electrons which can enable long-distance radio communication. It is composed of D, E and F layers, named in the order of increasing height. Figure 2 shows the designated D, E and F (F_1 and F_2) layers showing the Earth viewed from above the North geographic pole.

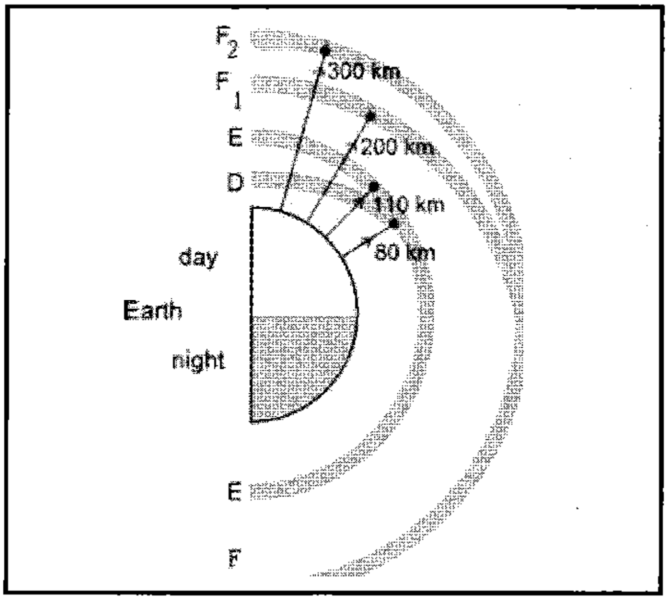

Figure 2 : Ionospheric layers as a function of height above the Earth's surface and local time (Antenna and Radio Wave Propagation, 2007)

During daytime, the radiation of the sun is high on the local atmosphere. At this time, all the layers will exist At nighttime, only the F_2 layer will be seen since the other three layers (D, E and F_1) almost completely disappear due to the recombination process. This layer will then be termed simply as the F layer.

For transionospheric propagation, higher frequencies than the HF band (i.e. VHF band or higher) can be used in order to reach the satellites, which are orbiting above the ionosphere. Due to the presence of electron density in the ionosphere, the radio wave that propagates through the ionosphere will be refracted. It will continuously refract due to the varying index of refraction in the ionosphere. The ionospheric horizontal gradient is the variation of electron density with latitude and longitude, which can cause the azimuthal deviation of the GPS ray path. It can either increase or decrease the propagation time of the GPS signal depending on the path or trajectory of the signal with respect to the gradient direction, which is normally termed as group path or group delay. However, when there is no variation in the composition of electron density along the GPS propagation ray, it is termed as ionosphere without horizontal gradient. This medium of ionosphere without ionospheric horizontal gradient is also known as homogeneous medium.

The IPP is the altitude or the assumed altitude of the centroid of mass of the ionosphere (Rama Rao et al., 2006). In other word, IPP is the point at which the LOS has effectively penetrated the ionosphere at the altitude of maximum electron density (Datta Barua et al., 2002). However, the IPP at the Equatorial region is at the altitude of about 250km while at mid latitude, the IPP is about 350km (Sripathi et al. 2008). Since L_1 and L_2 represent different value of carrier frequencies, the intersections of those GPS carrier frequencies at IPP are different. This difference also due to the presence of ionospheric horizontal gradient. It means, both GPS carrier frequencies are propagating in different paths.

METHODOLOGY

In this project, Jones 3D Ray Tracing program (Jones and Stephenson, 1975) has been used to show the difference in distance in between the intersection of IPP for both L_1 and L_2 at two different geographical locations. This versatile three-dimensional ray tracing computer program can trace radio waves through an ionospheric medium (transionospheric) whose refractive index varies continuously in three dimensions; altitude, latitude or longitude. By fixing the location of the Earth station, the elevation angle and the azimuth angle, a radio wave can be traced to the GPS satellite at an altitude of about 20 200km. Ray tracing program often requires a realistic ionospheric mathematical model, which must be a continuous model with no singularities, in order to represent the exact formation of the ionosphere either with or without horizontal gradient. So, in this project, the 3D mathematical model that has been used to represent the formation of the ionosphere with and without gradient was taken from (Strangeways H.J. and Nagarajoo K, 2005). Then, by doing the ray tracing, the intersection point or IPP for L_1 and L_2 can be obtained by 'fixing' an altitude at equatorial and mid-latitude region. These altitudes can be termed as IPP altitudes (Sripathi et al. 2008). Whenever the GPS ray reaches its respective IPP altitude, the ray tracing program will be halted in order to determine the latitude and longitude of that IPP. In this project, the ray tracing program was executed at different elevation angles; from 15º (cut-off elevation angle) to 85º, at every 15º of interval. The Earth station was 'fixed' at equatorial and mid latitude region in order to see the effect of ionospheric horizontal gradient to the intersection of L_1 and L_2 at IPP at both these regions.

RESULTS AND ANALYSIS

(A) Variation in Group path for Without and With Ionospheric Horizontal Gradient at Different Elevation Angles

As for the preliminary case, the ray tracing program was executed at different elevation angles to determine the group path or group delay of the GPS ray (L_1) to reach GPS satellite for the case without and and with ionospheric horizontal gradient. The Earth station was fixed at 5º of latitude and 110º of longitude with 30º of azimuth angle. The group paths that have been obtained at different elevation angles (at every interval of 15º) is shown in Table I below.

Table I : The group path of L_1 for without and with ionospheric horizontal gradient at different elevation angles

Elevation (°)	Group Path (km) Without Gradient	Group Path (km) With Gradient
15	24162.5397	24162.5465
30	22769.4390	22769.4433
45	21644.3143	21644.3172
60	20824.7181	20824.7215
75	20328.541	20328.5442
85	20181.0645	20181.0675

From the Table I above, it is known that with the presence of ionospheric horiozontal gradient, the group path or group delay of the GPS ray is greater when compare with the case without ionospheric horizontal gradient. This is because the L_1 propagates towards the direction with greater composition of electron density for with gradient case (azimuth angle = 30º). That causes the ray to experience higher group delay when compare with the case without ionospheric horizontal gradient. The difference in the group path is shown in Table II below.

Table II : The difference in the group path (?) of L_1 for without and with ionospheric horizontal gradient at different elevation angles

Elevation (°)	? in Group Path (m)
15	6.8
30	4.3
45	3.9
60	3.4
75	3.2
85	3.0

From Table II, it can be seen that at the lowest elevation angle, the difference in the group delay is the greatest. This has shown that at lower elevation angle, the ionospheric horizontal gradient has greater effect to the GPS ray.

(B) L_1 and L_2 at IPP of Mid -Latitude and Equatorial regions

In this section, the Jones 3D Ray Tracing program was used to observe the difference in L_1 and L_2 at IPP over the mid -latitude and equatorial regions. The ray tracing program was executed by setting the Earth station at the mid-latitude region (35º, 100º) and the equatorial region (3º, 100º). For the mid -latitude region, 350km was chosen as the altitude of the IPP, whereas for the equatorial region, the IPP was fixed at 250km. For both cases, the azimuth and elevation angles were chosen to be 30º and 15º, respectively. Then, the locations of IPP (latitude and longitude) for both L_1 and L_2 were obtained at both the mid-latitude and equatorial regions. The simulations were carried out taking into account both without and with ionospheric horizontal gradients. On top of that, the group paths for both L_1 and L_2 to reach the IPP were also obtained.

Table III below shows the location of the IPP (latitude and longitude) that was obtained for L_1 and L_2 for both mid-latitude and equatorial regions for the no gradient case. It also shows the group path of L_1 and L_2 until they reach their respective IPP.

Table III : The group path and location of GPS rays at IPP over the Mid-Latitude and Equatorial regions for without ionospheric horizontal gradient

Location	GPS Carrier Frequency (MHz)	Group Path (km)	(Latitude °, Longitude °) at IPP
Mid-Lat	L_1	1053.9217	(41.04°, 176.29°)
	L_2	1053.9362	(41.04°, 176.29°)
Equatorial	L_1	794.5044	(3.43°, 124.10°)
	L_2	794.52	(3.43°, 124.10°)

The nomenclature of the contents of Table IV is similar to the contents of Table III, except that it is for the case with ionospheric horizontal gradient.

Table IV : The group path and location of GPS rays at IPP over the Mid-Latitude and Equatorial regions for with ionospheric horizontal gradient

Location	GPS Carrier Frequency (MHz)	Group Path (km)	(Latitude°, Longitude °) at IPP
Mid-Lat	L_1	1053.9362	(41.03833968°, 176.28637310°)
	L_2	1053.9828	(41.03865081°, 176.28662282°)
Equatorial	L_1	794.4971	(4.00797692°, 125.41775245°)
	L_2	794.5471	(4.01055731°, 125.41840560°)

From Table III and IV, it can be seen that the group path for L_2 is always greater than L_1 at both mid latitude and equatorial regions for both without and with ionospheric horizontal gradient. This is because lower carrier frequency (L_2) takes longer path to propagate through the ionosphere compare to the higher carrier frequency (L_1) due to the effect of refraction. On top of that, the group path for with ionospheric horizontal gradient case always greater than without ionospheric horizontal gradient case. This is due to the direction of the GPS ray which experiences greater content of electron density (higher horizontal gradient).

In Table V below, the distance (in unit meter) in between L_1 and L_2 of IPP at mid-latitude and equatorial regions for without ionospheric horizontal gradient is given. The difference in between the group path of L_1 and L_2 that reaches its respective IPP are also given. As can be seen, over the equatorial region, the distance between L_1 and L_2 can go up to about 19m.

Table V : Distance and group path difference between L_1 and L_2 at Mid-Latitude and Equatorial regions for without ionospheric horizontal gradient

Location	Distance (m)	? Group Path (m)
Mid-Lat	17.805	14.5
Equatorial	18.805	15.6

Table VI below has the same nomenclature as Table V above, except that it is for the case with ionospheric horizontal gradient.

Table VI : Distance and group path difference between L_1 and L_2 at Mid-Latitude and Equatorial regions for with ionospheric horizontal gradient

Location	Distance (m)	? Group Path (m)
Mid-Lat	40.487	46.6
Equatorial	295.738	49.9

From Tables V and VI, it can be seen that the distance between L_1 and L_2 at IPP for with ionospheric horizontal gradient is very much greater than without ionospheric horizontal gradient. It is also has been proved that the presence of ionospheric horizontal gradient need to be taken into account whenever determining the position on the Earth using GPS.

CONCLUSIONS

In this project, the Jones 3D Ray Tracing program has been used to show that both L_1 and L_2 propagates in different routes to reach its respective IPP. The difference in the path is due to the composition of electron density in the ionosphere and the presence of ionospheric horizontal gradient, which causes lower carrier frequency (L_2) to refract greater than the higher carrier frequency (L_1).

From the results also, it could be seen that the distance at IPP between L_1 and L_2 over the equatorial region is greater than the mid-latitude regions. This is due to the presence of greater ionospheric horizontal gradient over the equatorial region than the mid latitude region. However, in order to get better results, the modeling of the ionosphere should be more accurate, especially over the equatorial region.

ACKNOWLEDGMENT

The author is grateful to UTHM for providing Short Term Research Grant (Vote Number: 0660) which was very helpful in term of financial assistance to conduct this research. Thanks also to WARAS Research Centre, UTHM, for making available ionospheric observation data.

REFERENCE

[1] Bilitza D., International Reference Ionosphere – IRI 2001. http://modelweb.gsfc.nasa.gov/models/iri.html (accessed on April 1, 2009)

[2] Datta-Barua S., Walter T, Pullen S., Luo M., Blanch J., and Enge P., 'Using WAAS ionospheric data to estimate LAAS short baseline gradients', Proceedings of the ION 2002 NTM, Anaheim, CA., pp. 523-530, January 2002.

[3] Ioannides R.T., 'Ionospheric modelling and path determination for GPS range-finding correction', PhD Thesis, School of Electronic and Electrical Engineering, University of Leeds, 2002.

[4] Jones R. M., and Stephenson J., 'A versatile three-dimensional ray tracing computer program for radio waves in the ionosphere', OT report 75-76, U.S. Department of Commerce, October 1975.

[5] McNamara L.F., 'Radio amateurs guide to the ionosphere', Florida, USA: Krieger Publishing Company, 1994

[6] Rama Rao, P. V. S., Niranjan, K., Prasad, D. S. V. V. D., Gopi Krishna, S., and Uma, G., 'On the validity of the ionospheric pierce point (IPP) altitude of 350 km in the Indian equatorial and low-latitude sector', Ann. Geophys., 24, 2159-2168, 2006

[7] Strangeways H.J., Nagarajoo K., '3D Gradient Effects on Transionospheric paths (such as from GPS) determined by ray-tracing in a 3-D IRI ionosphere', Paper presented at

2nd European Space Weather Week ESWW II, ESA-ESTEC, Noordwijk, The Netherlands, 14-18 November 2005.

[8] Sripathi, S., Bose, S., Patra, A. K., Pant, T. K., Kakad, B., and Bhattacharyya, A., 'Simultaneous observations of ESF irregularities over Indian region using radar and GPS', Ann. Geophys., 26, 3197-3213, 2008.